11.—Orientation and Composition of Plagioclase in a Basic Charnockite from Bunker Bay, Western Australia

By John G. Kay*

Manuscript received—19th June, 1962

Bunker Bay is an area of excellent coastal outcrop of high-grade metamorphic rocks. A clinopyroxene-orthopyroxene-hornblende-plagioclase granulite from the western shores of the bay is described, and attention drawn to the facts:

(i) the plagioclase grains are strongly oriented with *a*-axes parallel to the *b* tectonic direction.

(ii) the plagioclase grains belong to a population of variable composition that forms a normal distribution from An_{37} to An_{56}. A chemical analysis of the plagioclase is given.

Introduction

Cape Naturaliste is the northern limit of an elongate belt of Precambrian gneiss and granulite that extends sixty miles south to Cape Leeuwin (see Fig. 1). This "Leeuwin-Naturaliste Precambrian ridge" is an extension of the main Western Australian Precambrian Shield, from which it is separated by a belt of sediments, some 40 miles in width, that constitutes the southern part of the Perth Basin. Bunker Bay is situated two miles east of Cape Naturaliste, and marks the axial region of a large-scale north-plunging anticline, the nose of which forms the prominence of Cape Naturaliste.

Published references to Cape Naturaliste have described the geology in broad outline only. Saint-Smith (1912) in the course of a comprehensive areal survey recognised the general rock types and their fundamental relationships as a Precambrian granite-gneiss basement overlain in part by limestone. Woodward (1916) mentioned some tectonic aspects of the area, and Aurousseau (1926, p. 625) commented on Bunker Bay in these terms: "The exposures at Bunker Bay are admirable and should attract the attention of a student of metamorphism who wishes to make an intensive study of a small area. None could be more suitable than Bunker Bay." Prider (1952 and 1955) considered the Cape Leeuwin-Cape Naturaliste Precambrian belt to be the southern part of a more comprehensive "Leeuwin-Greenough Block", which, in relation to the remainder of the Western Australian Shield constituted the "West Coast Province."

A detailed investigation was recently undertaken by the present author and the results of this work are the substance of a forthcoming paper. The following is a summary of the main features. The basement rocks are a succession of gneisses and granulites of highly variable mineralogy. The dominant rocks are poorly fissile, and range from granitic through adamellitic to granodioritic in bulk mineralogical composition. Mafic components are one, or a combination of two or more of hornblende, biotite, orthopyroxene, clinopyroxene, garnet, and very rarely, fayalite. Interbanded with these rocks are bands of basic granulite typically containing the assemblage hornblende-clinopyroxene-plagioclase or hornblende-clinopyroxene-orthopyroxene-plagioclase. The overall succession probably represents a sedimentary pile with concordant and possibly some discordant basic igneous rocks that has undergone regional metamorphism. This has produced rocks of granulite and upper almandine-amphibolite facies, with some evidence that the latter facies has developed by downgrading of the former.

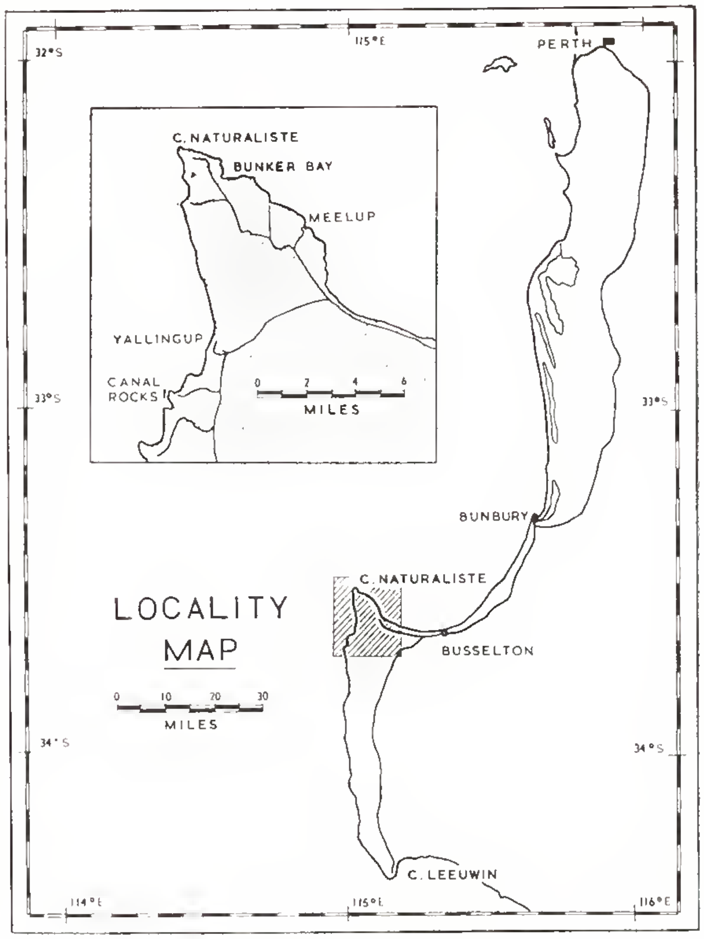

Fig. 1.—Locality Map.

The rocks contain a foliation which is more likely a consequence of isoclinal folding than a relict pre-metamorphism feature. This foliation is warped into large-scale folds plunging north and overturned to the west. Linear structures are present and these essentially parallel the axes of associated drag folds. The lineation plunges 20°-40° in a direction that varies from north-east to 20° west of north. At Bunker Bay the lineation consistently plunges 30°-37° in the direction 350°.

Following prolonged erosion, the basement rocks have been lateritized and later covered on their western flank by a varying but appreciable thickness of aeolian Quaternary calcarenite. This forms part of the Coastal Limestone of Western Australia, and has been described by Fairbridge and Teichert (1953, pp. 68-87).

* Department of Geology, University of Western Australia Nedlands, Western Australia.

Petrography

The remainder of this paper sets out the results of a detailed investigation of plagioclase from basic granulites, 39407* and 39409, from Bunker Bay. These rocks outcrop as two closely spaced parallel bands, each several yards in width, extending into the western waters of the Bay. Specimen 39407 is representative of the southern band, and 39409 of the northern band. At low tide and after prolonged sand scour the two bands can be seen to form a single U-shaped mass with a joining segment that in part transgresses the surrounding foliation. Outcrop boundaries of the two bands strike 77° and dip 33°-37° N, and parallel the foliation of surrounding garnetiferous, biotitic and hornblendic gneiss.

Specimen 39407 is an almost black rock, of somewhat "greasy" appearance, with medium-grained saccharoidal texture, and devoid of obvious mineralogical banding. A well-developed preferred orientation of hornblende and pyroxene prisms plunges 33° in the direction 350°. This lineation lies within, and parallel to the dip of a poorly developed foliation. Thin veins of hornblendite traverse the granulite, and many of these strike 67° and dip 70° S.

In thin section specimen 39407 is seen to have a xenomorphic granular texture with a strongly oriented fabric of the ferromagnesian minerals and plagioclase. The mineralogy of the rock is:

Plagioclase (40.1%†)—andesine, An_{45}‡; generally in anhedral, equi-dimensional grains between 0.25 mm and 0.5 mm in diameter; non-antiperthitic and unzoned; $2V/\gamma = 80°$; albite and acline twinning well developed; inclusions of euhedral apatite; *a*-axes strongly oriented (see Fig. 2); extinction $X' \wedge 010$ in sections $\perp a = 24.0° \pm 5°$ (see Fig. 4).

Hornblende (27.6%)—as anhedral grains, in cross section 0.3 mm x 0.3 mm and commonly 1 mm in length; *c*-axes show distinct orientation, and the fabric of 200 grains is shown in Fig. 3; strongly pleochroic in shades of brown, with $\alpha =$ mid yellow-brown, $\beta =$ very deep brown, $\gamma =$ very deep brown; $\alpha < \beta = \gamma$, $\beta = 1.680 \pm 0.003$; $2V/\alpha$ = approximately 80°; $\gamma \wedge c = 20°$.

Orthopyroxene (16.9%)—ferrohypersthene, Fs_{52}; generally as anhedral grains 0.25 mm x 0.25 mm; distinctly pleochroic with $\alpha =$ pale pink, $\beta =$ pale yellow, $\gamma =$ pale aqua-green; $\gamma = 1.730 \pm 0.002$; $\alpha = 1.714 \pm 0.002$; $\gamma - \alpha = 0.016$; $2V/\alpha = 52° \pm 1°$.

Clinopyroxene (11.0%)—salite Wo_{48} En_{33} Fs_{19}; similar in habit to ferrohypersthene, pale yellow-green and faintly pleochroic $\gamma = 1.719 \pm 0.003$; $2V/\gamma = 56.5° \pm 0.5°$; r > v (weak); $\gamma \wedge c = 42°$.

Iron Ores (4.4%)—(undifferentiated); as small anhedral grains throughout the rock; in part showing minor leucoxenization.

Apatite is a minor accessory, and occurs in small discrete anhedra, and as rare scattered inclusions in the plagioclase. K-feldspar, quartz and zircon are absent.

The secondary hornblendic bands contain amphibole optically similar to that in the enclosing granulite, i.e. pleochroic with $\alpha =$ mid brownish yellow, $\beta =$ very deep brown, $\gamma =$ very deep brown, $\alpha < \beta = \gamma$; $\gamma = 1.703 \pm 0.003$, $\alpha = 1.685 \pm 0.004$; $\gamma - \alpha = 0.018 \pm 0.007$.

The granulite is cut by small tabular pegmatites of secretion origin. These are rather discontinuous, and normally less than 3 inches thick. Plagioclase is the dominant mineral—forming approximately 80% by volume and determined optically as andesine, zoned somewhat irregularly from An_{45} at the centres of grains to An_{30} at the margins. Quartz and untwinned microcline occur as interplagioclase fillings. Hypersthene (Fs_{35}) is present to the extent of 5%, and clinopyroxene frequently forms a margin to the pegmatites. An interesting accessory is zircon; interesting because of its absence from the studied samples of enclosing granulite. Zirconium has apparently concentrated into the secreted pegmatitic phase.

Specimen 39409 conforms in general to the description for 39407. In detail, however, the plagioclase (andesine, An_{45}; 47.8%) and orthopyroxene (ferrohypersthene, Fs_{52}; 18.5%) content is greater than in 39407, the hornblende (14.7%) content is considerably lower, and the clinopyroxene ($En_{36.5}$, Fs_{21}, $Wo_{42.5}$; 11.9%) content is similar.

Aurousseau (1926, p. 624) published a brief account of a "hornblende-orthopyroxene-plagioclase amphibolite" from Bunker Bay, and included a chemical analysis of the specimen. Although an exact field location for the analysed rock is not given, there can be little doubt that the sample was taken from the granulite (39407 or 39409) described in this paper. The C.I.P.W. norm for Aurousseau's analysed rock is given by Wilson (1958, p. 76).

Orientation of Plagioclase

The plagioclase grains in basic granulites from Cape Naturaliste possess a strongly preferred orientation. Evidence of this is the disproportionate abundance of grains approximately parallel to 100 that are revealed in thin-sections cut normal to the *b*-lineation. In order to investigate this fabric, the *a*-axis position for each of 200 grains of plagioclase in a thin-section from specimen 39407 was determined using a 4-axis universal stage. Fig. 2 is a reproduction of the fabric diagram obtained, and shows a well-developed orientation of *a*-axes with an average plunge of 20° in the direction 350°.

A similar analysis was carried out on the attitude of c-axes for 200 grains of hornblende from the same thin-section. The result is shown in Fig. 3, which indicates a strong mean alignment plunging 20° in the direction 348°. The similarity of the fabrics in Figs. 2 and 3 is striking.

* The specimens are catalogued and housed in the rock collection of the Department of Geology, University of Western Australia.

† All such percentages are volume percentage obtained from parallel line traverses on section cut normal to lineation.

‡ Mineral compositions were estimated by reference to the following graphical data: for plagioclase, Winchell and Winchell (1951, p. 283); for orthopyroxene, Hess (1952); for clinopyroxene, Hess (1949, p. 634).

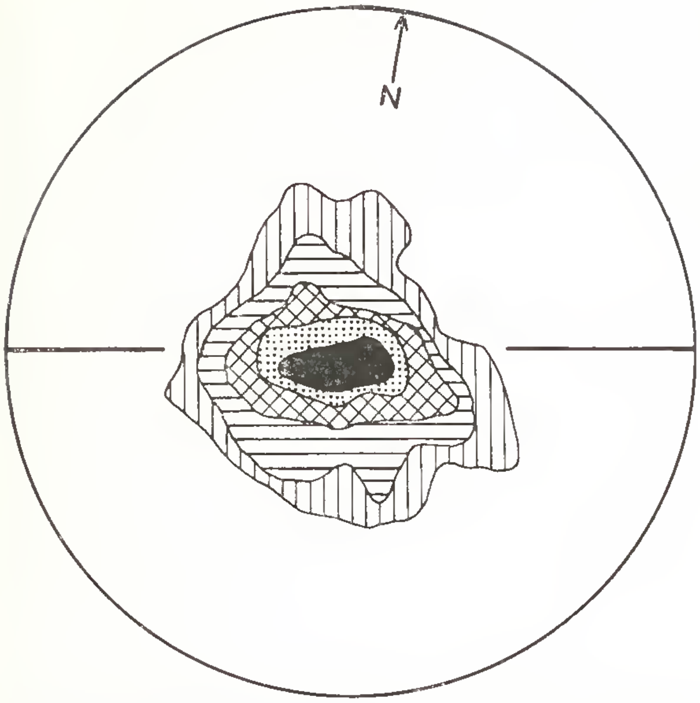

Fig. 2.—Orientation diagram of 200 andesine *a*-axes from 39407. The fabric is a linear orientation plunging 20° on an azimuth 350°. Contours at 1%, 3%, 5%, 10%, 15% (including 16.5% maximum). The horizontal line represents a plane, strike 80°, dip 15° N.

Specimen 39407 is strongly lineated in a macroscopic sense due to alignment of prismatic minerals, in particular, hornblende. Throughout the Cape Naturaliste area such lineations parallel drag fold axes and can thus be taken as *b*-lineations. The lineation in specimen 39407 is not accompanied by drag folds, but in view of the relationship existing elsewhere is clearly a *b*-lineation.

It may be concluded that in this rock the *a*-axes of plagioclase have preferentially aligned during metamorphism parallel to the *c*-axes of hornblende and thus parallel to the *b*-tectonic direction. The direction of preferred orientation of the plagioclase *a*-axes defines a *b*-lineation. This same conclusion was reached for rocks in the Ornö Huvud by Wenk (1937).

The macroscopic lineation of 39407, measured on the poorly developed foliation, plunges 33° in the direction 350°. A plunge discrepancy of 13° is thus apparent between the *b*-lineation as measured in the field and measured by petrofabric methods. This discrepancy may indicate that the foliation on which field measurements were made is not the true *a* - *b* plane, but may also mean no more than the sum of sampling and experimental errors.

Extinction in sections normal to *a*

During the fabric analysis of plagioclase in specimen 39407, extinction values X′ ∧ 010 in sections normal to *a* were obtained for 200 grains. Fig. 4 is a plot of extinction values (X′ ∧ 010 in section ⊥ *a*) against percentage of readings. The result conforms to a somewhat skewed normal distribution around a mean of 24° - 25°, but with a spread from 20° to 30°. This range corresponds to a variation from andesine An_{37} to labradorite An_{56}, with a mean at approximately andesine An_{45}. Although most readings are close to the mean, a significant number depart from the mean by amounts outside the limits of experimental error (estimated to be less than ± 2°). This serves to emphasise that in the course of normal petrographic investigations the use of a single extinction measurement to establish bulk plagioclase composition could lead to considerable error. The difficulty also extends to other isomorphous groups such as the pyroxenes, and should be taken into account when assessing the value of data obtained from single grains.

TABLE I

Analyses of plagioclase from Bunker Bay

	I	II
SiO_2	55.01	55.55
Al_2O_3	29.14	28.41
(Fe_2O_3, FeO) as Fe_2O_3	0.16	0.02
CaO	9.01	9.53
MgO	Nil	Nil
SrO	0.18	0.10
K_2O	0.27	0.66
Na_2O	5.63	5.73
H_2O+	0.23	Nil
	99.63	100.00

I. Bulk plagioclase from 39407, Bunker Bay, W.A.
II. Bulk plagioclase from 39409, Bunker Bay, W.A.
Anal. J. G. Kay and I. D. Martin.

A chemical analysis of the bulk plagioclase from 39407 is presented in Table 1 (column 1). In terms of end-member composition calculated using standard formulae, the feldspar is

	%
albite	47.63
anorthite	44.69
K-feldspar	1.59
"Sr-feldspar"	0.56
	94.47

The composition determined chemically and expressed as anorthite per cent. ($An_{44.7}$) agrees very well with the mean composition determined optically by the method X′ ∧ 010 in section ⊥ *a* (An_{45}).

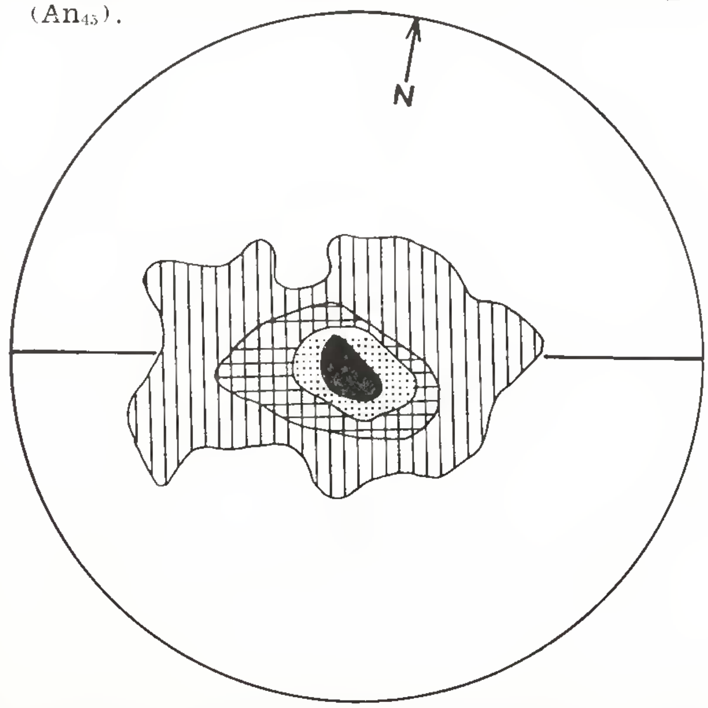

Fig. 3.—Orientation diagram of 200 hornblende *c*-axes from 39407. The fabric is a linear orientation plunging 20° in the direction 350°. Contours at 1%, 5%, 10%, 15% (including 17.5% maximum). The horizontal line represents a plane, strike 80°, dip. 15° N.
Rare grains (not shown) have *c*-axes approximately normal to the indicated linear maximum.

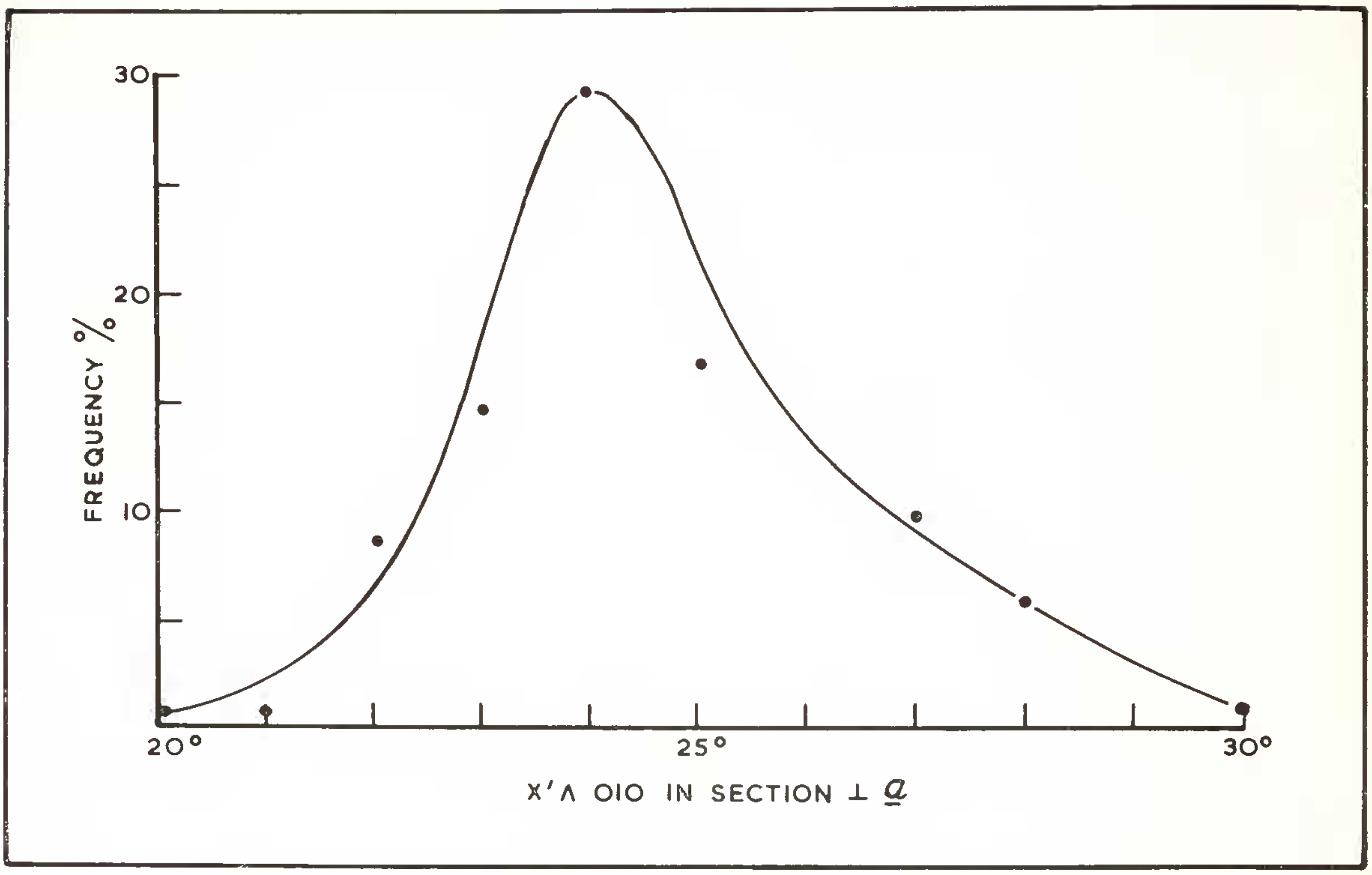

Fig. 4.—Graph showing the frequency of readings for the extinction X' ∧ 010 in section normal to *a* for 200 andesine grains in 39407. Values range from 20° to 30°, but with a strong maximum near 24°.

The deficiency of 5.53% revealed by end-member summation is a problem in view of the apparent purity of the analysed sample. This deficiency was initially attributed to incorrect alkali determinations, but a check analysis indicated no significant error. Furthermore, after satisfying the end-member requirements, there is a surplus of 3.03% Al_2O_3 and 1.71% SiO_2. These, together with the Fe_2O_3 and H_2O of the analysis may indicate undetected alteration products and/or inclusions.

An analysis was also carried out on plagioclase from specimen 39409, a rock which is mineralogically and texturally very similar to 39407. The plagioclase of 39409 (Table 1, column II) responds more satisfactorily to end-member summation:

	%
albite	48.48
anorthite	47.27
K-feldspar	3.90
"Sr-feldspar"	0.31
	99.96

For this analysis Al_2O_3 exceeds by 0.86% the amount required to fulfil end-member requirements, whereas the available SiO_2 is 0.82% less than the amount required. Using the method X'∧010 in section ⊥ *a*, the average composition for this plagioclase was determined as andesine An_{45}.

Acknowledgments

I would like to thank Mr. I. D. Martin who assisted with the chemical analysis of the plagioclase. Professor R. T. Prider and Dr. G. J. H. McCall read the manuscript and offered helpful suggestions. The work was carried out during the tenure of a Hackett Scholarship at the University of Western Australia.

References

Aurousseau, M. (1926).—Analyses of three Australian rocks. *Proc. Linn. Soc. N.S.W.*, 51: 614-626.

Cloos, E. (1946).—"Lineation." *Mem. Geol. Soc. Amer.* 18.

Fairbridge, R. W., and Teichert, C. (1953).—Soil horizons and marine bands in the Coastal Limestone of Western Australia. *J. Roy. Soc. N.S.W.* 86: 68-87.

Hess, H. H. (1949).—Chemical composition and optical properties of common clinopyroxene, part 1, *Amer. Min.*, 34: 621-666.

Hess, H. H. (1952).—Orthopyroxenes of the Bushveld type, ion substitutions and changes in unit cell dimensions. *Amer. J. Sci.* Bowen Vol.: 173-187.

Prider, R. T. (1952).—South-west Yilgarnia. *Sir D. Mawson Anniv. Vol., Univ. Adelaide:* 143-151.

———— (1955).—The Pre-Cambrian succession in Western Australia. *Proc. Pan-Ind. Ocean Sci. Congr.*, Perth, Sect. C: 69-78.

Saint-Smith, E. C. (1912).—A geological reconnaissance of a portion of the South-West Division of Western Australia. *Bull. Geol. Surv. W. Aust.* 44.

Wenk, E. (1937).—Zur Genese der Bändergneise von Ornö Huvud. *Bull. Geol. Instn Upsala* XXVI: 53-89.

Winchell, A. and Winchell, H. (1951).—"Elements of Optical Mineralogy." 4th Ed. (Wiley: New York.)

Wilson, A. F. (1958).—Advances in the knowledge of the structure and petrology of the Precambrian rocks of south-western Australia. *J. Roy. Soc. W. Aust.* 41: 57-83.

Woodward, H. P. (1916).—Notes on a portion of the South-West Division. *Annu. Progr. Rep. Geol. Surv. W. Aust.:* 10-11.